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ANALYSIS OF A SPLITTING SEVERE THUNDERSTORM USING THE WSR-88D

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1. INTRODUCTION

During the late afternoon of March 23, 1995 severe thunderstorms developed rapidly and moved east and southeast across parts of southeast North Carolina. The thunderstorms produced golf ball size hail and winds greater than 50 kt (26 m s^{-1}) at numerous locations. One particular storm complex split into two separate severe cells with one cell moving right of the mean wind, and the other cell moving left of the mean wind. Doppler radar storm-relative velocity data indicated cyclonic rotation in the low and midlevels of the right-moving storm and anticyclonic rotation in the midlevels of the left-moving storm.

The process by which a thunderstorm undergoes a split into two distinct "mirror image" cells has been researched (Rotunno 1981) and modeled (Weisman and Klemp 1984). A conceptual model of the splitting process is shown in Fig. 1. This type of storm evolution is most likely to be observed in an environment characterized by moderate to strong instability, and strong unidirectional wind shear. Numerous studies have shown that, in the northern hemisphere, the left-moving cell acquires anticyclonic rotation in the midlevels, while the right-moving cell takes on the characteristic cyclonic rotation of a classic supercell thunderstorm (Glass and Truett 1993; Kleya 1993; Andra 1993; Nielsen-Gammon and Read 1995). When the wind direction veers with height and there is moderate to strong speed shear, the development of the right-moving cell is favored with the left-moving cell usually dissipating (Klemp and Wilhelmson 1978; Brandes 1984; Davies-Jones 1984).

Burgess (1981) studied the frequency of splitting thunderstorms among storms observed by National Severe Storms Laboratory (NSSL) Doppler radar between 1972 and 1976. Left-moving, anticyclonically rotating, severe thunderstorms were quite rare in the data set studied. With the deployment of the WSR-88D (Weather Surveillance Radar-1988 Doppler) to National Weather Service (NWS) offices across the country there has been an increase in the number of split thunderstorms observed and reported.

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All of the case studies reviewed in the preparation of this paper were of thunderstorm splits that occurred in the Great Plains, Midwest, or Gulf Coast. No studies were found of recent observed splits occurring in the southeastern United States. Many thunderstorm split studies have concentrated on a post-split analysis of the storms. In contrast, this paper will describe the actual splitting process as it appeared in reflectivity and velocity data from the Wilmington, NC (KLTX) WSR-88D radar. The observed structure will be compared with the conceptual model and the storm-relative wind field will be examined with the use of a hodograph derived from a local upper-air sounding.

2. SYNOPTIC SCALE FEATURES AND STORM ENVIRONMENT

The 1200 UTC 23 March 1995 500 mb analysis (not shown) indicated a weak short wave and 70 kt (36 m s^{-1}) jet streak across the Ohio Valley. Scattered thunderstorms were occurring ahead of the short wave over parts of northern Kentucky. Numerical models were in good agreement showing the short wave, and associated jet streak, moving rapidly southeast to the southeast coast of North Carolina by 0000 UTC 24 March.

At the surface, a center of low pressure was located in south-central Kentucky. A warm front stretched from the low pressure center southeast across the southern Appalachian Mountains and along the border between South and North Carolina. The warm front had slowed its northeastward progression during the night and had become stationary by 1200 UTC. A low-level southwesterly wind maximum of 40 kt (21 m s^{-1}) was observed at 850 mb across northern Alabama and Georgia at 1200 UTC. This low-level jet was contributing to the advection of warm air and moisture into the region south of the warm front. Abundant surface moisture was also evident across South Carolina, with morning dewpoint temperatures between 15°C and 17°C.

Morning soundings (not shown) across the southeast U.S. confirmed that a warm unstable airmass was in place south of the warm front. The 1200 UTC sounding for Charleston, South Carolina (CHS), modified for the forecast maximum temperature and dewpoint, gave a surface-based CAPE of 2000 J/ kg. North of the warm front, at Newport, North Carolina (MHX), the modified sounding showed no surface-based CAPE. However, a calculation of CAPE above the capping inversion (around 800 mb) gave a value of 290 J/kg. This indicated that elevated instability did exist to the north of the warm front. Vertical wind profiles from the CHS and MHX soundings showed strong unidirectional shear from 850 mb through 300 mb. The Bulk Richardson Number (BRN) for the modified CHS sounding was 47 indicating the shear and potential buoyancy were nearly ideal for mesocyclone development and persistence (Weisman and Klemp 1982). In summary, conditions over the eastern Carolinas favored the development of strong convection along and near the stalled warm front.

As the day progressed the sky remained clear south of the front. This allowed for maximum solar insolation with surface temperatures nearing 30°C. Surface dewpoints in the warm air reached 15°C to 20°C. With support from the upper level short wave, the surface low pressure center was deepening over western North Carolina by early afternoon. By 2100 UTC the low-level convergence associated with the surface low and warm front, combined with the strong surface heating, was enough to eliminate the capping inversion and initiate convection just east of Charlotte, North Carolina (CLT). As the surface low moved rapidly southeast along the warm front, an increase in surface moisture convergence was followed by an increase in the intensity of the convection. Shortly after 2230 UTC, a severe thunderstorm produced 1.9 cm hail which covered the ground at Maxton, North Carolina (150 km east southeast of CLT).

3. WSR-88D REFLECTIVITY AND VELOCITY DATA

Figures 2a through 2d show 0.5 degree base reflectivity of the splitting severe thunderstorm between 2222 and 2252 UTC. Figure 2a shows the polar grid overlaid on the graphic to indicate that the radar is southeast of the storm complex. Each frame is centered on the storm as it moved to the southeast during this 30 minute period. Annotations have been made on each frame indicating the general location of the splitting cells and their associated circulations. Storm R moved to the right of the mean wind acquiring a deep cyclonic rotation. Storm L became the left-mover and showed anticyclonic rotation in the midlevels.

As the storm complex evolves, tight reflectivity gradients can be seen on both the northern and southern flanks (Fig. 2b). The tight reflectivity gradients indicate that the storm complex has strong storm-relative inflow from both a northerly and southerly direction. In the 1.5 degree reflectivity scans (not shown) higher reflectivity values (dBZ) were noted above the inflow on the southern flank of the storm complex (i.e. midlevel overhang). There was no midlevel overhang observed on the northern flank of the storm complex.

In the sequence of reflectivity images (2a through 2d) there is an area in the middle of storms R and L which shows decreasing reflectivity values (dBZ) with time. This represents the initial convective cell weakening with time and will be discussed in more detail in Section 4.

By 2252 UTC (Fig. 2d) the severe thunderstorm has split into two cells. Storm R moved to the southeast at 35-40 kt (18-21m s^{-1}) becoming larger and more intense. There were numerous reports of large hail, frequent lightning, and wind damage with storm R until it moved out to sea south of Wilmington, NC. The reflectivity and storm-relative velocity characteristics of storm R were similar to those described by Glass and Truett (1993) for a right-moving split storm that occurred in east central Missouri in 1992. A thunderstorm with this type of multi- and supercellular structure has also been described as a "hybrid" storm by Nelson and Knight (1987).

Storm L, while not as large as storm R, was nonetheless severe. After 2252 UTC (Fig. 2d) storm L tracked east at 40 kt (21 m s^{-1}) bringing golf ball size hail and damaging winds to many locations. Storm L lasted for over an hour before moving out over the Atlantic Ocean and dissipating. Along its entire track, storm L showed a tight low-level reflectivity gradient on the east-northeast flank and anticyclonic rotation in the middle levels.

The midlevel storm-relative motion (SRM) within the thunderstorm complex is shown in Figs. 3a through 3d. Figures 3a through 3c show the 1.5 degree elevation angle SRM from 2222 to 2242 UTC. Figure 3d is the SRM for the 2.4 degree elevation angle at 2252 UTC. The higher angle in Fig. 3d was chosen to keep the radar beam at approximately the same height within the storm as it approached the radar. As in Fig. 2, the radar is located to the southeast of the storm complex. The center of the radar beam is about 3.6 km above ground level in the middle of each image of Fig. 3.

Figure 3a appears to show a chaotic image of storm-relative velocity. However, on closer inspection, a few features stand out. Perhaps the most noticeable features in the velocity pattern are the strong inbound values of 30-40 kt (15-21 m s^{-1}) on the north and south flanks of the storm. These areas correspond to the outside edges of the cyclonic and anticyclonic circulations respectively. Moving northward across the velocity pattern depicted in Fig. 3b, four interconnected circulations can be inferred. This is the same midlevel pattern shown in the conceptual model in Fig. 1. The circulation pattern is a direct result of the horizontal vorticity (due to the vertical wind shear) being tilted into the vertical by the thunderstorm updraft. If the updraft speed increases with height, the air column is stretched through vertical divergence. A feedback process occurs whereby the increase in vertical divergence contributes to an increase in horizontal convergence in the lower levels of the storm. This, in turn, increases the rotation of the updraft through conservation of angular momentum. The stronger rotation can further strengthen the updraft due to a resulting pressure gradient force which develops within the thunderstorm, several kilometers above the surface (Rotunno 1981).

Although not shown, the 0.5 degree SRM was dominated by outbound values of relative velocity. This indicated a southeasterly storm-relative inflow at the low levels. At elevation angles above 2.4 degrees the SRM showed inbound values of relative velocity and this indicated a northwesterly storm-relative outflow in the upper levels. Referring to the storm relative flow in Fig. 1 it can be seen that the storm-relative motion observed by Doppler radar matches the storm-relative wind field depicted in the conceptual model for a splitting storm.

A radar-identified mesocyclone occurred in Storm R at 2237 UTC (just before Fig. 3c). The mesocyclone was associated with the main updraft of storm R and lasted well over one hour beyond the split. Using the Norman, Oklahoma NWS Forecast Office Modified NSSL Mesocyclone Recognition Guidelines (Andra 1996, personal communication), the mesocyclone rotational velocity varied from moderate to strong (25-45 kt, 13-23 m s^{-1}) throughout the lifetime of storm R. The mesocyclone depth varied from 2-5 km. A tornado warning was issued for storm R at 2346 UTC, almost one hour after Fig. 3d. At this time storm R was located in a remote area and no tornado was ever confirmed. Storm-relative velocity values increased, and the mesocyclone appeared to strengthen as storm R came closer to the radar.

One reason the mesocyclone appeared to strengthen could be related to the change in radar aspect ratio, and increased sampling of the circulation. The appearance and apparent strength of a circulation can change as the radar beamwidth decreases with decreasing range to the target (Burgess 1976). It is possible that the mesocyclone within storm R was just as strong at longer ranges from the radar, but the circulation was not accurately resolved until the storm came closer to the radar.

The mesoscale anticyclonic rotation which developed in the middle levels of storm L could only be detected by the radar operator. The WSR-88D mesocyclone algorithm was not designed to automatically alert the operator to anticyclonic shear (Federal Meteorological Handbook No. 11 1991). Anticyclonic rotational velocity in storm L varied from weak to moderate (10-35 kt, 5-18 m s^{-1}) for well over one hour. In the lowest levels of the storm the anticyclonic rotational velocity remained weak (10-15 kt, 5-9 m s^{-1}). Anticyclonic divergence was noted near the top of storm L and very likely contributed to a strong updraft and the production of large hail with this thunderstorm (Burgess and Ray 1986).

4. LOCAL HODOGRAPH

The 0000 UTC 24 March 1995 sounding from Newport, NC (MHX) was used to construct the local hodograph for this event. Figure 4 shows the "straight line" hodograph. The vectors marked "R" and "L" on the hodograph are the observed storm motions for storms R and L after the split. The surface to 6 km mean wind is denoted by the "M" near the center of the hodograph. The shear vector is the dark line from the surface (sfc) through 7 km with a dot every 500 meters.

The hodograph is an important tool for thunderstorm forecasting (Doswell 1988). A hodograph can be used to determine the possible character of forecast convection. Given adequate convective instability, a weak shear environment usually leads to short-lived "pulse type" thunderstorms (Prentice 1993). Moderate to strong shear is usually a requirement for isolated steady-state convection. A hodograph that shows clockwise turning with height indicates an environment favorable for the development of cyclonic rotation within a thunderstorm updraft (Davies-Jones 1984). When a thunderstorm develops in such a sheared environment there is a good possibility that horizontal vorticity (produced by the low-level vertical wind shear) can be tilted into the updraft of the storm to aid in the production of cyclonic rotation (positive vertical vorticity). A hodograph that shows counterclockwise turning with height would indicate the possibility for anticyclonic rotation within a thunderstorm updraft.

The straight line hodograph in this case would indicate the strong possibility of splitting storms (Weisman and Klemp 1984, 1986). The split of the storm complex occurs when the intense rain and hail, in the center of the initial cell, contribute to the cold downdraft. As the downdraft reaches the surface and moves away from the base of the storm, favorable inflow to the initial convection is diminished (Fig. 2c and 2d). If the environment remains unstable after the initial convection, new convection usually develops along the outflow boundary. With splitting thunderstorms, two convective cells develop along the outflow boundary; one on either side of the initial thunderstorm. Strong unidirectional vertical wind shear allows the new convective cells an equal chance at maintaining low-level inflow. This is the nature of split thunderstorm propagation in an environment favorable for steady-state convection.

After a split occurs in a straight line hodograph environment, the storms become mirror images of one another. The left-moving storm is now to the left of the shear vector and encounters a "counterclockwise hodograph" environment. Given a strong enough updraft, anticyclonic rotation is enhanced within the left-moving storm. The right-moving storm is now to the right of the shear vector and encounters a "clockwise hodograph" environment. Cyclonic rotation within the updraft of the right-mover will be enhanced. The greater a storm motion vector deviates from the mean wind shear vector, the greater the storm-relative inflow for that storm. The greater the storm-relative inflow, the stronger the thunderstorm updraft. A stronger thunderstorm updraft is more likely to acquire rotation through the tilting of horizontal vorticity.

Based on the hodograph in Fig. 4, storm R had greater storm-relative inflow through a deeper layer of atmosphere than storm L. Storm L had strong low-level inflow but deep layer inflow was almost non-existent. It follows that storm R developed a stronger updraft, and deeper, stronger, rotation. Storm R also moved through an area with greater instability and stronger low-level convergence and this may also have contributed to its larger size, and more intense character, after the split occurred.

5. SUMMARY

The thunderstorms in this case developed rapidly in response to a surface low pressure center moving southeast across North Carolina. The strength of the instability and the straight line hodograph indicated an environment which was favorable for splitting thunderstorms. Once storms appeared on radar, the midlevel storm-relative velocity product for one storm complex showed a circulation pattern consistent with the conceptual model for splitting storms. Reflectivity information, over a period of one-half hour, indicated that two storms were evolving from one complex. Although not alerted by the radar algorithms, the radar operator could determine the anticyclonic rotation in the left-moving cell by using the midlevel SRM product. Aware of the splitting storms, and the updraft rotation in both storms, the radar operator could expect the possibility of two severe thunderstorms instead of one.

A good assessment of the pre-storm environment can aid in successful thunderstorm forecasting. Moisture availability, instability, and lift are required for convection to develop. Vertical wind shear is required for the convection to persist and propagate once it does develop. With an understanding of how these atmospheric features affect thunderstorm behavior, the forecaster will be better prepared when echoes begin to appear on the radar.

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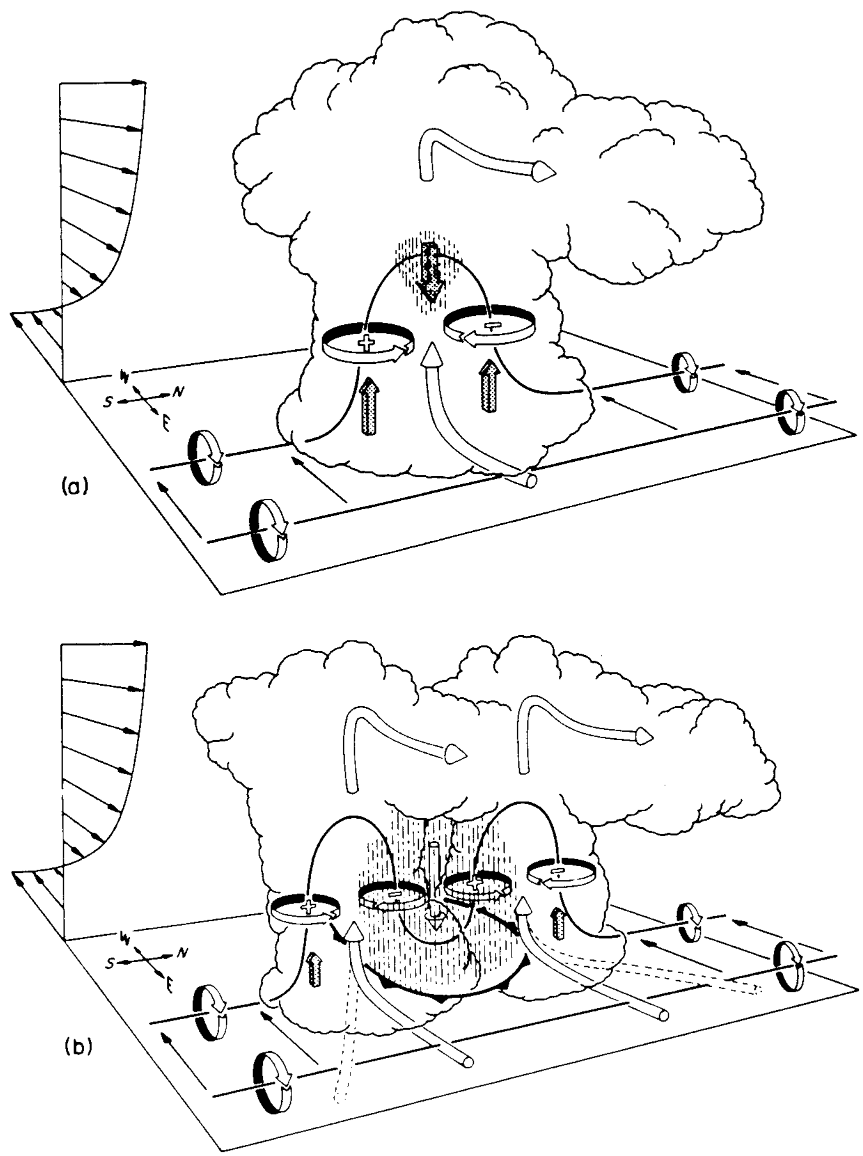

Figure 1. Conceptual model of a splitting thunderstorm. (A) Initial convection with cyclonic (+) and anticyclonic (-) circulations. (B) Splitting stage with four interconnected circulations (adapted by Klemp 1987, from Rotunno 1981).

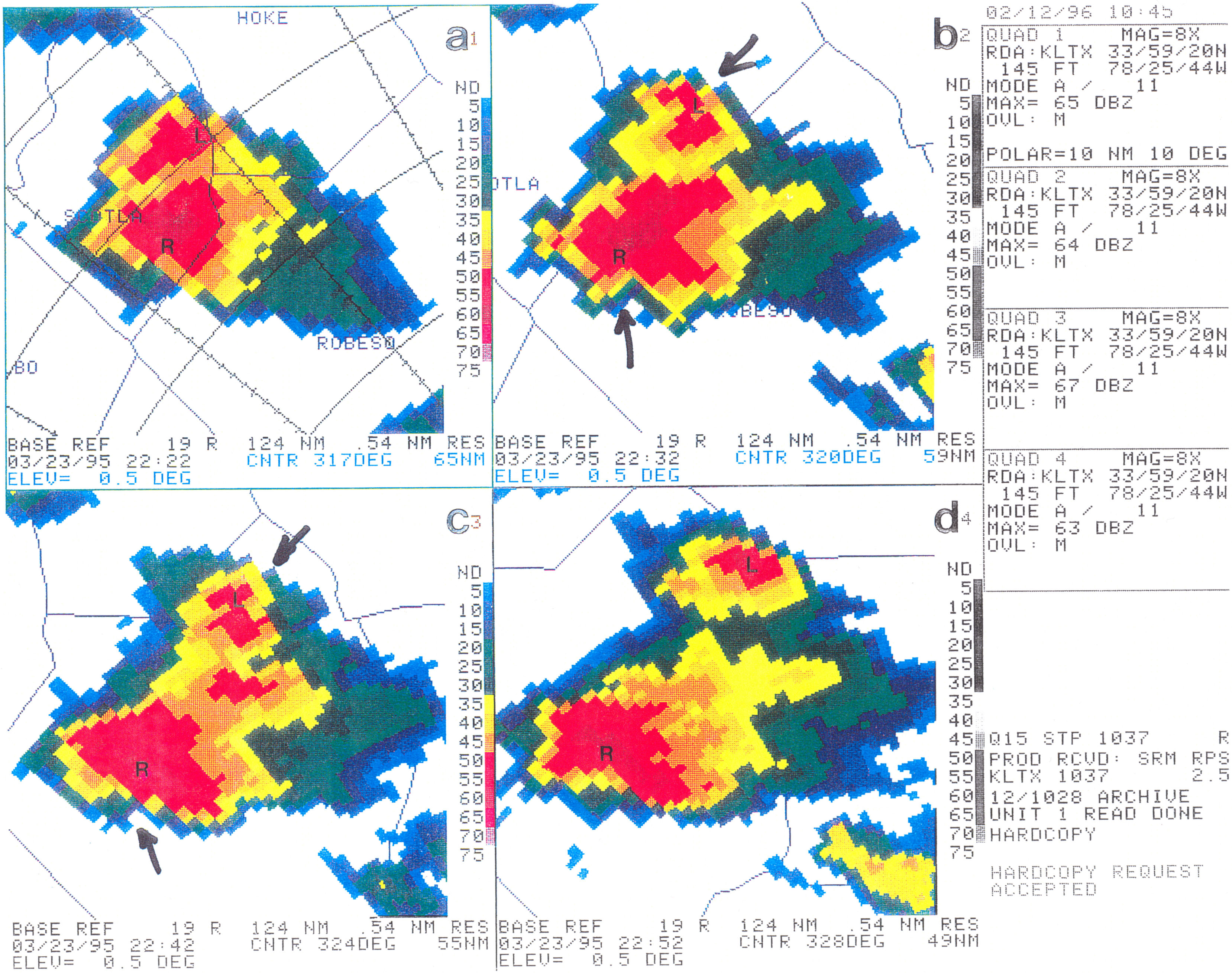

Figure 2. Time sequence of the Wilmington, NC (KLTX), WSR-88D base reflectivity product at .5 degrees elevation angle. The sequence is at 10-minute intervals beginning at 2222 UTC 23 March 1995. Each frame is centered on the storm. The color bar on the right of each panel depicts intervals of reflectivity in dBZ. The "**R**" indicates the right-moving storm and the "**L**" indicates the left-moving storm. The arrows in (b) and (c) indicate areas of strong reflectivity gradient.

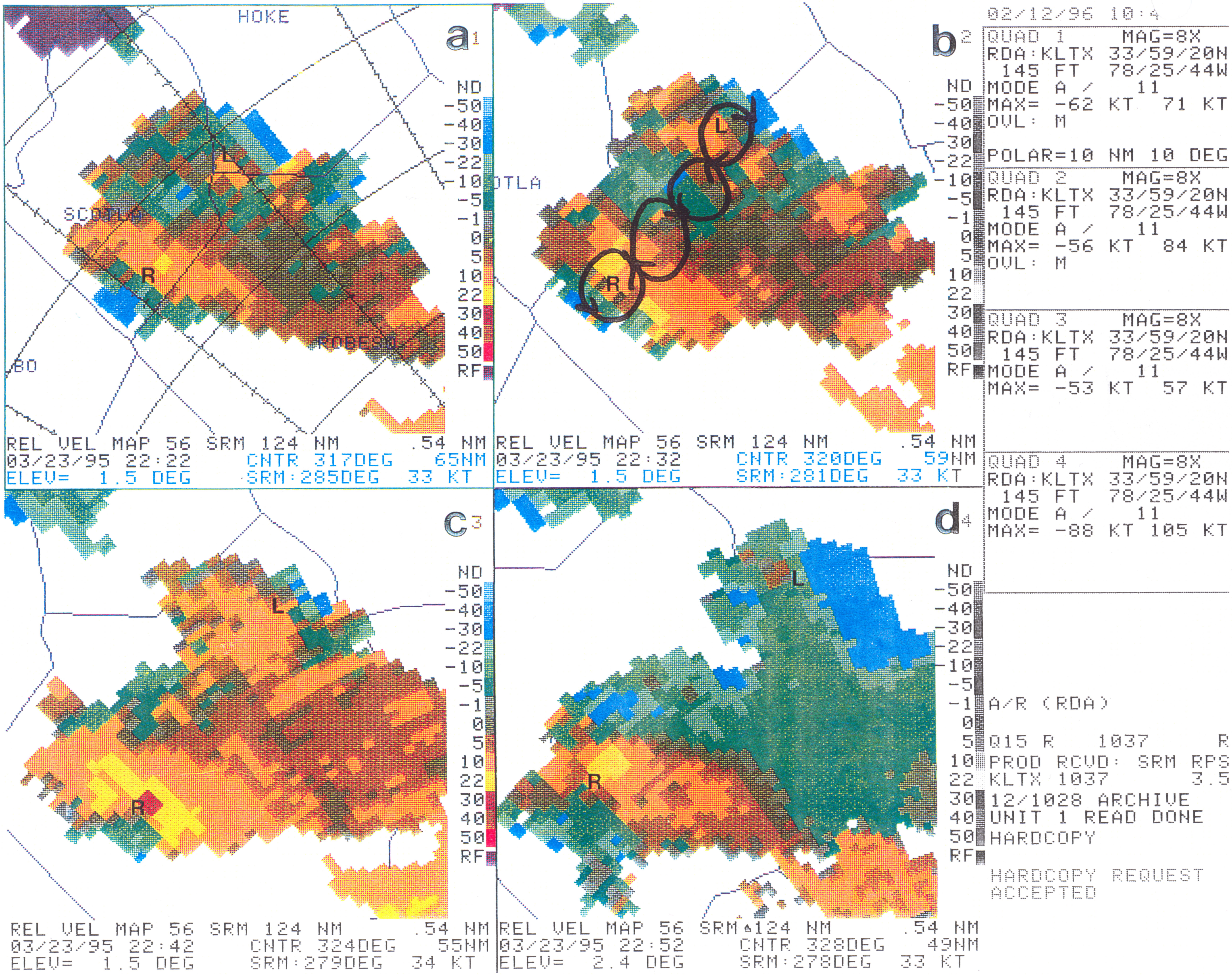

Figure 3. Time sequence of the Wilmington, NC (KLTX), WSR-88D storm-relative motion product. The sequence is at 10-minute intervals beginning at 2222UTC 23 March 1995 (same as in Fig. 2). Panels (a), (b), and (c) are at 1.5 degrees elevation angle. Panel (d) is at 2.4 degrees elevation angle. The color bar on the right of each panel depicts intervals of radial velocity in knots with negative values indicating flow toward the radar and positive values away from the radar. The "**R**" indicates the right-moving storm and the "**L**" indicates the left-moving storm. The circular arrows in (b) indicate the flow pattern.

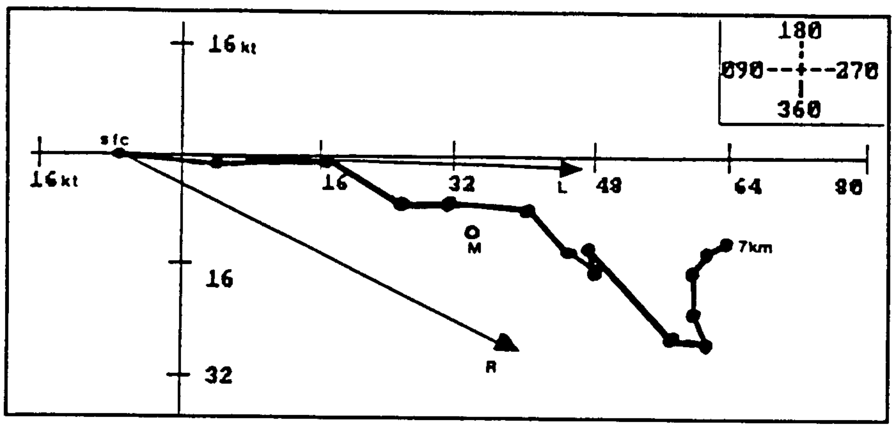

Figure 4. Local hodograph with storm motion vectors marked "R" and "L", 0 to 6 km mean wind marked "M", and shear vector dotted every 500 meters from the surface to 7 km.